A MAGNETIC SPECTROMETER FOR CHARGED PARTICLES

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ABSTRACT. A Siegbahn-Svartholm type magnetic spectrometer, designed for focussing of ~ 1 Mev protons and developed in this laboratory is described with constructional details

Results of the measurement of the magnetic field and its gradient are given. Performance of the instrument in the low field region is tested with the conversion electron spectrum of Cs-137 source Experiments showing the resolution, dispersion and the axial focussing properties of the spectrometer are presented.

INTRODUCTION

Since the use of a $\sqrt{2}\,\pi$ focussing inhomogeneous magnetic analyser for β-spectrometry for the first time by Siegbahn and Svartholm (1946), a number of such electromagnets has been constructed in different laboratories for spectrometry of high energy ions and β-particles

The theories on this type of two directional focussing magnetic analysers are fully developed by Siegbahn and Svartholm, Shull and Dennison (1947), Judd (1950), Rosenblum (1950), Verster (1950) and others

Theories show that at any angle other than $\sqrt{2}\,\pi$, these magnetic analysers may also be used for focussing of charged particles Based on this idea nuclear spectrometers have been constructed by Rubin and Snyder *et al* (1950), Rubin and Sachs (1955), Mileikowsky (1953) and others with a focussing angle π. In these cases, the transmission of the instrument fairly decreases, so as $\sqrt{2}\,\pi$ focussing angle is preferred for β-spectrometry work.

In this paper, we have described such a $\sqrt{2}\,\pi$ focussing magnetic spectrometer, designed for moderately high intensity mass spectrometry and may be useful for focussing energetic heavy ions with a limit upto ~ 1 Mev protons.

THEORETICAL CONSIDERATIONS

The idea of two-directional focussing of charged particles with an inhomogeneous magnetic analyser of the shape

$$H_z = H_0 \left(\frac{r_0}{r} \right)^n \qquad \ldots \quad (1)$$

where H_0 is the field at the mean radius r_0, the field index $n = -\frac{r_0}{H_0}\frac{dH}{dr}$ of the radially varying field H, is due to Kerst and Serber (1941) in connection with the focussing of the synchrotron oscillations Expanding eqn (1) we have

$$H_z = H_0(1 - \alpha\delta + \beta\delta^2 \quad) \qquad \ldots \quad (2)$$

where $\alpha = n, \quad \beta = \frac{n^2+n}{2}, \quad \delta = \frac{r-r_0}{r}$

where $r = r_0 + \delta r, \quad r_0,$ being the mean radius

For $n = \frac{1}{2}$, the charged particles are focussed in radial and axial directions at an angle $\sqrt{2}\,\pi$. The term β in equation (2) determines the order of focussing For $\beta = \frac{3}{8}$ or $\frac{1}{8}$, the second order aberration in axial or radial direction respectively, can be eliminated. Rosenblum (1950) suggested the value of β equal to $\frac{1}{4}$ for an average first order focussing in both the directions Higher order terms for improved resolution has been considered by Verster (1950) Stoker *et al* (1954) Lee-whiting and Taylor (1947) Lehr (1955) and others

For $\beta = \frac{1}{4}$, the $\sqrt{2}\,\pi$ focussing magnetic analyser gives the spherical aberration

$$\delta_{ab} = \tfrac{2}{3} r_0(\gamma_1^2+\gamma_2^2) \qquad (3)$$

where $$\gamma_{1,2} = \frac{h_{1,2}}{r_0\sqrt{2}}$$

h_1 and h_2 are the radial and axial apertures of the chamber of the spectrometer respectively.

For angles other than $\sqrt{2}\,\pi$, focussing of the charged particles has been considered by Judd (1950), Rosenblum (1950) and others for $n = \frac{1}{2}$. In these cases, unlike $\sqrt{2}\,\pi$ focussing angle, the source and the detector are to be placed outside the magnetic field. For other values of n, the possibilities of using these magnetic analysers have been considered by Sternheimer (1953) and others as Alsceveky *et al* (1955). However, from the general expression for the solid angle

$$\frac{\Omega}{A} = \left[\, l^4 + \frac{1-l^2}{n(1-n)} \,\right]^{-\frac{1}{2}}. \quad \text{sterad} \qquad (4)$$

where Ar_0^2 is the maximum available cross section area for the ion path, we see that for any focussing angle other than $\sqrt{2}\,\pi$, due to the finite distance l of the source from the field boundary, the solid angle factor is diminished. For a focussing angle $\sqrt{2}\,\pi$, $l = 0$ such as $\Omega = \frac{A}{2}$ sterad and is maximum compared to any other focussing angle with the field index $n = 0.5$.

DESIGN AND CONSTRUCTION OF THE MAGNET

Due considerations were given to the different types of inhomogeneous magnets before the present manget was constructed. It was found that for high intensity ion-spectrometry with a moderate resolution a $\sqrt{2}\pi$ focussing magnetic analyser will be more efficient than any other type. A closed cylindrical type magnet has been used by Arbman and Svartholm (1955) for β-spectrometry and such types are better in respect of the stray field, however, we chose a central core type, so that the cost of magnetic materials is less for a bigger spectrometer as required for heavy ions.

The magnetic analyser has been constructed with a central core 406 mm dia, 254 mm height, two circular yokes 100 mm thick, 430 mm dia. Two annular pole pieces 430 mm O.D., 330 mm I.D., mean radius $r_0 = 381$ mm.

The magnet is cast by Messrs Bhartia Electric Steel Co. Private Limited, Calcutta, with a special iron with 0·08% - 0·12% carbon content. The pole pieces are given a gardient, so that $\eta = 2°$ where η is the angle of the surface to the symmetry plane and the gap width is slightly greater than 50 mm, so as $\beta = 1/4$, is satisfied at least in the region of $r_0 = 381$ mm

We should mention that the dimensions of the above described magnet is not optimum, and it would be better to use a core of larger diameter. But considering the space for the coil and the cost of the magnetic material, we have limited our design to the above dimensions

After preliminary measurements on the field gradient, two guard rings 430 mm I.D., 470 mm O.D., tapered at an angle 7° are inserted to the outside boundary of the pole faces to avoid the stray fringing fields

The exciting coils consist of five pancakes each having 4000 turns of 20 S.W G. double glass served silicone bonded copper wire, wrapped with glass cloth and impregnated with silicone 996 varnish for attaining high insulation One of the pancakes has 200 turns less for providing insulating materials, decided to be used after the design. The coils have total d.c. resistance of 800 Ω and are given power from a stabilised high voltage supply of 200V—1.5 kV and max. current 1.25 amp. In this circuit 6336 double triodes (Chatham) are used as series tubes, and 5651 for reference voltage, the power supply has a voltage stabilisation ~ 0·1%. The weight of the magnet is 3000lbs. and that of the coil 450 lbs.

MEASUREMENT OF THE MAGNETIC FIELD AND ITS GRADIENT

The magnetic field is measured with varying current at the mean radius r_0 with a fluxmeter (Norma). The field vs current curve (figure 1) shows that the magnet may be used for the spectrometry work with $H_0 r_0 \sim 144$K gauss-cm.

For measuring the field gradient, of the above type of magnets, rotating search coil methods have been employed by Hedgran (1951), Lamb and Rother-

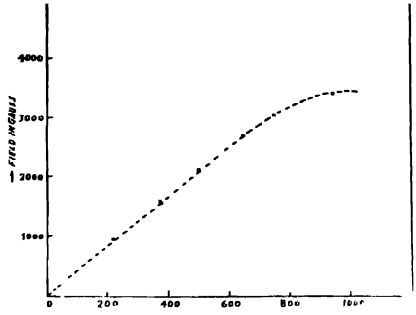

Fig. 1. Field vs current curve

ford (1951), Langer and Scott (1950). Null reading flip coil method has been used by Buechner *et al* (1948), Fetcher and Rubin (1955) for measuring the gradient of the inhomogeneous magnets. We followed the latter method because it required

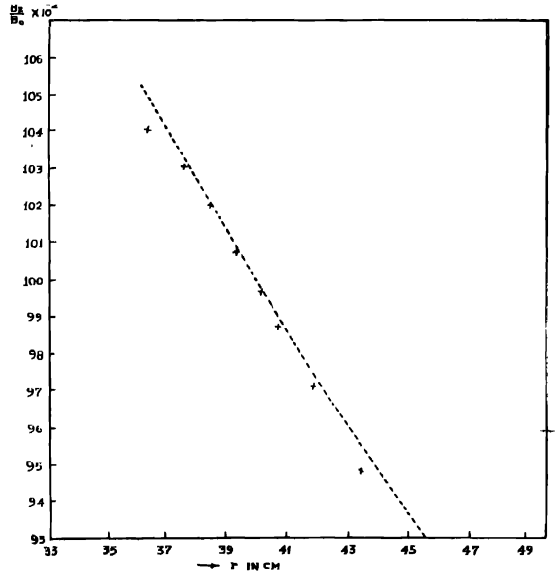

Fig. 2 $\frac{B_z}{B_o}$ - r curve, (Theo - - -, expt ×,)

less precision in mechanical construction. We used two search coils, mounted on a brass tube and driven by a 1/100 h.p. small motor coupled to the end of the tube The rotation is limited to 180° by a switch which stops the motor when the 180° rotation is complete. One of the coils (2500 turns) is fixed at $r_o = 381$ mm and the other one (850 turns) is movable. The circuit, which is employed for balancing the output voltages from the search coils using sensitive galvanometer as a null indicater is similar to Fetcher *et al* (1955). The resistance divider consists of a decade resistor (100 Ω per step) and a 100 Ω helipot. Null point is recorded for different points of the magnetic pole piece setting, the movable coil at those points with the fixed coil at $r_o = 381$ mm with the different values of H_o. The ratio was calculated from the resistance potentiometer for different values of r. Figure 2 shows the $\frac{B_z}{B_o} - r$ curve experimentally found with the finally shaped pole pieces. The accuracy of the measurement is not better than 02%, because of the broadening of the null point due to the phase shift in the search coils. The curve theoretically calculated with $\beta = 1/4$ in equation(2) is compared with the experimental points, so a small part of the pole faces seems to be available for a first order two-directional focussing of the charged particles.

VACUUM EQUIPMENTS

The annular shaped vacuum chamber is made of $\frac{5}{32}$ inch thick brass sheets and welded to fit the pole gap. It extends a few cms over the 270° extension of the pole pieces for facilating the introduction of the source and the detector. The entrance and exit slit-holders for the charged particles are mounted within the chamber at an angle $\sqrt{2}\pi$ before welding it. Three baffles are inserted within the chamber at equidistant spacings between the slit-holders for avoiding scattering of the particles. The central one may also be used to place slits to reduce the radial and axial aperture of the spectrometer The baffles and the slit holders have approaches from the outside through the openings. All the openings are made vaccum tight with flanges and O-rings

The chamber is evacuated by a 6" diffusion pump backed by a mechanical pump. The speed of the diffusion pump is-180 litres per sec. at 10^{-4} mm. Hg. with a water cooled baffle. The limit of the vacuum attained is $\sim 1 \times 10^{-5}$ mm. Hg without the use of any low temperature cooling trap. The general view of the spectrometer with the vacuum equipments is given in figure 3.

PERFORMANCE

To test the performance of the spectrometer, a solution of chloride of Cs-137 was deposited on an aluminium plate, the width of the source being ~ 7 mm. The source was placed in the slit-holder of the spectrometer vacuum chamber and the conversion electron spectrum of 0.661 Mev γ is detected with a 1B85 (Victoreen)

Fig 3. General view of the spectrometer.

counter through a 3.2 mm slit at an angle $\sqrt{2}\pi$ at the detector side The magent is excited with acid cells in the following experiments. Figure 4 shows the resolved spectra of K and L lines at a solid angle $\backsim$ 0.4% sterad. the resolution attained

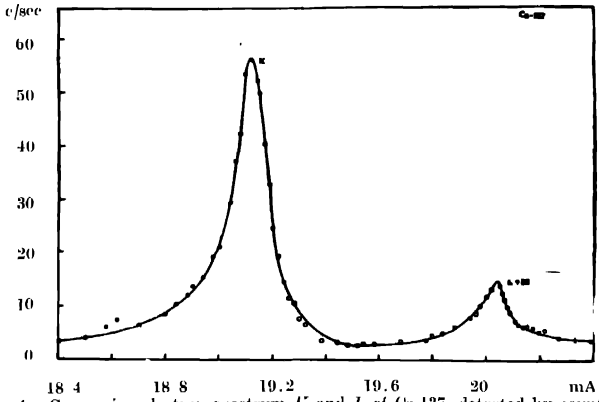

Fig. 4. Conversion electron spectrum K and L of Cs-137, detected by counter.

is 0.54% at the half-width compared to the theoretical resolution 0.42%, calculated from the formula,

$$\text{Resolution at half peak} = \frac{a + b + \delta_{ab}}{8r_0} \tag{5}$$

The radial aperture, $h_1 = 44$ mm and the axial aperture, $h_2 = 22$ mm determine the aberration, δ_{ab}. By reducing the apertures and the width of the source 'a' and that of the detector slit 'b', the resolution can further be increased. The experimental resolution obtained above is worse than the theoretical value due to the secondary radiations from the chamber walls and the source target itself. Some improvement may be expected by using a more suitable source target so that back scattering and such radiations are avoided.

The dispersion of a two-directional focussing magnetic analyser with $n = 0.5$ is twice that of a homogeneous magnet. It can be represented as

$$D = \frac{\delta s}{r_0}\Big|\frac{\delta p}{p} \tag{6}$$

where r_0 is the mean radius, δs is the distance between the peaks of the particles having momentum p and a difference in momentum δp. The dispersion of the magnetic spectrometer is tested with a (Ilford) G-5 nuclear emulsion (100μ) plate, placed in the detector side and is exposed to the conversion lines L and M of a narrower Cs-137 source. Since with this method a less intense beam can be detected, resolved L and M spectra are recorded. Figure 5 shows the L and M conversion lines scanned from an exposed plate according to the method adopted by Anatov

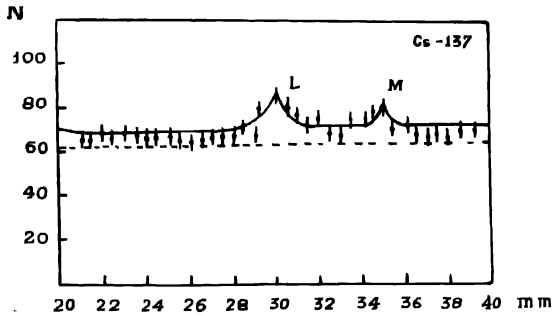

Fig. 5. L and M conversion lines of Cs-137 recorded by nuclear emulsion plates.

(1956) The number of electron tracks N plotted with the length of the plate in figure 5 includes the background counts determined from a plate without any exposure to the source. To attain accuracy in the estimation of the internal conversion coefficients from the spectra, with this method, it is better to attain an improved statistics from two or more plates exposed under the same conditions. However, from the scanning of a single plate with a Leitz Ortholux microscope

of magnification 1000, we have a distance of 5 ± 0.5mm between the peaks of L and M lines having energy difference 4.304 keV. As the plate makes an angle 10° to the plane, perpendicular to the optic axis for facilitating the detection of electrons, δs is equal to 4.92 ± 0.5 mm. in that plane. Thus

$$D = 3.8 \pm 0.4$$

This is to be compared to the theoretical value of D, which is 4 for such two directional $\sqrt{2}\pi$ focussing magnetic analysers

The axial focussing property of the magnetic spectrometer is also tested with the same source deposited on a cotton thread and placed lengthwise in the radial direction of the spectrometer. The sharpness of its image in figure 6 shows the

Fig. 6. The image of a cotton thread soaked with Cs-137 source placed lengthwise in the radial direction

existence of the axial focussing, attainable with this type of magnetic analysers. The less intense luminous part near the image is due to the cotton fibres of the thread.

The present magnetic spectrometer shows the possibility of its use for high resolution β-spectrometry work. With the stabilised power supply for exciting the magnet, the spectrometer is expected to focus $\sim$ 1 Mev protons as tested by the measurement of the field Measurement of the gradient also shows that a comparable resolution may be attained with high energy ions.

Further works, to test this instrument with a high intensity ion source and high accelerating voltage, are in progress.

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